Industrial Fuel Switching Feasibility Study

Project Zap – Electrification of Biscuit Production

Ref: 21126-R-02 v1.0.0

30/09/2022

For the attention of:

Directorate for Science and Innovation for Climate and Energy

Department for Business, Energy & Industrial Strategy

1 Victoria Street, London SW1H 0ET

2022 © 42 Technology Limited

Document Change History

Version	Changes from previous issue	Date
1.0.0	Final issue	30/09/22

Document Authors

Company	Authors	Contributions
Burton’s Foods Ltd.	Martin Beckford	Project lead
42T	Katie Doig, Dan Ahearn, Tim Hartley	Technical feasibility assessment of new solution compared to existing technology
Cambridge Sensor Innovation	Mark Williamson	Oven expert, review and oven design input

Executive Summary

Burton's Foods Limited has baked biscuits in the UK since 1935, with expertise spanning across a wide range of sweet and savoury biscuit types from cookies to chocolate biscuits, shortbread to jam sandwiches, cheesy baked bites to flatbreads. Industrial baking in the UK currently uses natural gas fired ovens to produce biscuits with the flavour, texture and appearance that consumers enjoy at an acceptable price. Electrification is believed to be the most likely route to de-carbonisation, given the UK's commitment to a zero-carbon electricity supply by 2035 and uncertainty over the availability, cost and timing of green hydrogen.

The purpose and aims of the feasibility study in Phase 1 were to characterise the current oven and capture the requirements of a technically and commercially viable electric oven. This would then be shared with potential vendors to aid the development of suitable solutions.

These aims were met with the testing and characterisation work that was done. The study characterised the thermal and humidity profile of an industrial baking line to explore the feasibility of electrical switching. In addition, the energy loss was characterised to determine the efficiency savings that would have to be present on a new electric oven to make it commercially competitive and viable compared to gas ovens. The technology development necessary from the current nearest best available offerings required to enable the switch was also estimated following discussions with current market leaders in electric ovens.

The study concluded that there are electric ovens commercially available that can replicate the quality of products that are produced on a gas fired oven. However, the current electric offerings would not be cost competitive with the incumbent technology as the efficiency improvements currently available do not make up for the price difference in fuels. This study has highlighted some areas where the efficiency savings required could be made, such reduced conduction losses in addition to a heat recovery system. A follow-on phase from this feasibility study would be to implement the efficiency reductions and heat recovery options identified in this phase. The aim of this would be to validate the performance improvements and to establish the lowest energy oven settings to successfully produce a range of products.

The study has provided a process and a tool by which other lines can be assessed and reconfigured using electrical heating technologies. The methodology that will be developed in the study can be adapted to other related applications to enable emissions reduction in those sectors too. This would potentially unlock large carbon savings from the cumulative effect of the fuel switching of multiple production lines and facilities, if the benefits can be validated in a cost competitive solution.

Contents

1. Feasibility Study Objectives

Industrial baking in the UK currently uses natural gas fired ovens to produce biscuits with the flavour, texture and appearance that consumers enjoy at an acceptable price. De-carbonising the industrial baking process whilst maintaining product properties and costs is challenging.

Electrification is likely the most viable route to de-carbonisation, given the UK's commitment to a zero-carbon electricity supply by 2035 and uncertainty over the availability, cost and timing of green hydrogen. This view is supported by the Food & Drink Federation in their 2020 report "Decarbonisation of heat across the food and drink manufacturing sector" [1].

Table 1 FDF Report: Implementation of decarbonisation theme. [1]

	2020	2025	2030	2035	2040	2045	2050
Boilers	Low carbon fuels, Renewables, Electrification (boilers or indirect heat users)			Low carbon fuels, Fully decarbonised gas, Hydrogen, Renewables, Electrification (boilers or indirect heat users)			
Direct Fired Overs	Electrification		Renewables, Electrification	Low carbon fuels, Fully decarbonised gas, Hydrogen, Renewables, Electrification			
Other Direct Fired	Electrification		Renewables, Electrification	Low carbon fuels, Fully decarbonised gas, Hydrogen, Renewables, Electrification			
CHP[5]	Renewables, Electrification (indirect heat users)			Low carbon fuels, Fully decarbonised gas, Hydrogen, Renewables			
Other	Electrification		Renewables, Electrification	Low carbon fuels, Fully decarbonised gas, Hydrogen, Renewables, Electrification			

Table 2 FDF Report: Generic barriers to implementation. [1]

Timeframe	Reasoning
2020-2030	• Cost of alternatives not yet competitive enough and like for like replacements made. • Lack of knowledge or confidence in electrification of some processes. • Availability of renewable sources. • Uncertainty about future energy sources.
2030-2040	• Cost of alternatives not yet competitive enough and replacement cycles are delayed. • Supply of decarbonised gas or hydrogen not yet established. • Availability of renewable sources. • Lack of knowledge or confidence in new technologies. • Product quality compromised with alternatives.
2040-2050	• Cost of alternatives not yet competitive enough and replacement cycles are delayed. • Supply of decarbonised gas or hydrogen not yet established in less populated areas. • Product quality compromised with alternatives.

The legacy fleet of gas fired ovens and variation in key parameters means that oven design and operation often relies on expert knowledge, especially how the oven is run and tuned in response to different ingredient batches and external environmental conditions. Replication of a baking process using electrical heating requires characterisation of the current process and equipment before an electrical equivalent system can be designed.

While there are some electrical ovens on the market, these are not optimised to specific requirements. Different technologies may be applied to each part of the baking process to produce a more efficient system, and better equipment design and insulation will also minimise losses. The total energy requirement must be minimised, not only for resource efficiency but also to mitigate against the higher unit cost of electricity over gas currently, likely local electricity grid constraints and electrical infrastructure investment required.

The objectives of this study were to:

- Characterise the thermal and humidity profile of an industrial baking line
- Explore the feasibility of electrical switching and the technology development necessary from the current nearest best available offerings required to enable the switch
- Identify and assess an implementation roadmap, including
  - Oven design principles and required engineering development
  - Pilot line development
  - Life-cycle cost analysis

All the objectives of the feasibility study were undertaken successfully. Characterisation of the current ovens was carried out. The results of this were used to identify opportunities for improved performance. Recommendations for the next step phases of work to demonstrate the recommendations of this study in practise were then set out. The potential reduction in Burton's Foods Limited greenhouse gas emissions has been estimated at up to 12,000t CO_2e per year, with a further opportunity at our sister business Fox's Biscuits.

1.1. Feasibility Study Work Packages

There were several areas of uncertainty that needed to be considered in order to assess the feasibility of switching Burton's Food's biscuit baking ovens from gas to electricity. These included the need to assess:

- Technical feasibility
- Commercial viability
- Whether product quality could be maintained

42T was involved in this study to investigate these areas of technical uncertainty and to interact with suppliers within the industry to evaluate current commercially available offerings. In addition to the investigation, 42T also provided potential solutions to bridge the gap between available equipment and processes and the solution required to make fuel switching viable.

In addition to the technical challenge of replicating the oven conditions to produce good quality products, there was a commercial aspect to the challenge. Electricity is currently substantially more expensive per kWh than natural gas, making a switch without any efficiency improvements not commercially viable. Therefore, this study also aimed to identify areas of loss in order to estimate the savings that could be made and if these savings could make switch to electric ovens commercially viable. Some of the obstacles which contribute to compounding the challenge in this area include the fact that the efficiency of the gas ovens currently in use was unknown and the range of ovens available on the market is relatively limited, particularly at the scale that Burton's Foods require.

To address these areas of uncertainty, a scope of work split into three packages was proposed. The first work package was to establish a requirements specification. This would identify all the questions that would need to be answered to ensure that a solution was fully viable, both commercially and technically. Some of the requirements would not be immediately answered, however, were useful to identify knowledge gaps.

The second work package was testing and oven characterisation. Using the requirements specification as a starting point a test plan was devised and executed, attempting to fully characterise the oven. This recorded the parameters believed to be responsible for product quality. In addition, this testing was used to develop a heat and mass balance for the oven, estimating the key loss areas.

Finally, a vendor assessment was conducted. This built on the requirements specification developed in the previous two work packages. The vendor assessment was used to estimate the gap between what was available in the market and what was required.

2. Main Findings

2.1. Technical Feasibility

2.1.1. Summary

To determine the potential for switching to electric heating methods for baking ovens, two avenues were explored: determining if the quality of the products was reproducible from gas to electric ovens and investigating the lifecycle economic assessment of electric ovens.

Four key parameters that can affect the quality of the finished output of the product were mapped for the existing oven:

- Heat flux
- Temperature
- Air speed
- Humidity

How these parameters varied over time during baking was recorded. The testing showed that there was a range of oven conditions that could produce the product of a desired quality. The current operational window was established through testing. There is potential for finding oven settings that reduce energy use within the operational window. This would have to be established with further testing on a new oven.

Exploring the commercial viability of the oven centred around the potential efficiency of an electric oven. With the cost of electricity substantially higher than natural gas per unit of heating energy, the new oven needed to have a substantial efficiency advantage to ensure that the product could be made without a substantial increase in cost to the consumer. The oven being investigated was modelled, calculating the energy inputs and outputs, to determine the efficiency and source of losses. This was used as a baseline and to assess the potential for improvement.

2.1.2. Introduction

The biscuit making process has several steps, all of which have an important role for resulting quality of the product. This report will focus only on the baking process. However, the steps are all interlinked, meaning that a change in any part of the process can affect those further down the process. Factors such as amount of moisture in the flour, or the homogeneity of the mix can also affect the necessary baking parameters to achieve acceptable product. This therefore means that both the current oven and any oven of the future will need to have some flexibility in the baking conditions to adapt to the changing inputs from earlier in the process.

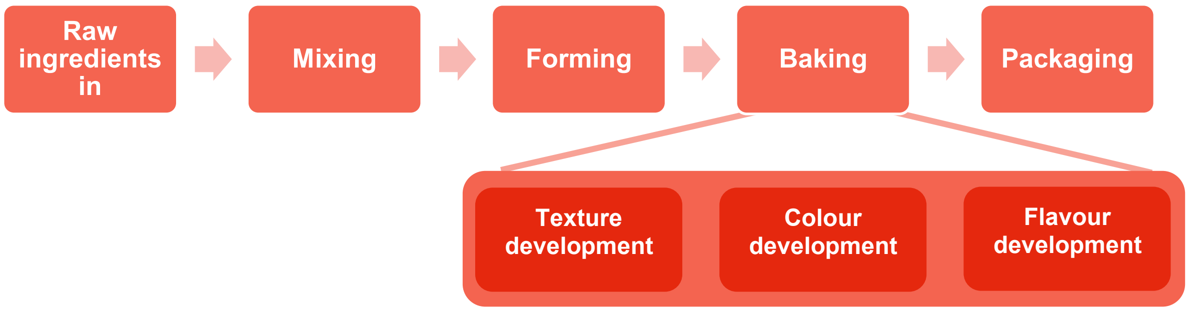


Figure 1 Biscuit making process steps

2.1.3. Quality Investigation Testing

Introduction

The first challenge in replacing gas fired ovens with electric, was to determine if the electric heating could produce products of the same quality. To do this the oven was characterised.

According to literature, the four key parameters that can affect the quality of the finished output of the product are: heat flux, temperature, air speed and humidity. As the baking process involves chemical reactions that take place within the dough pieces, there is also a time element to these parameters. How long the product is exposed to the baking conditions and how the conditions vary along the oven are key pieces of information that need to be known to completely characterise the existing oven.

Ovens transfer heat to the biscuits through a mixture of convective, radiative and conductive heat flux. For direct gas fired ovens, the ratio of the two is controlled by the gas input rate, and the amount of air recirculation and extraction rate. A minimum extraction rate must be maintained to ensure combustion gases are not vented into the workspace around the oven, giving a minimum convection rate. Electric heating elements produce radiative heating and convective heat flux can be achieved electrically heated forced hot air over the product surface. Both ovens are expected to be capable of producing the same temperature and heat flux characteristics for the products on an example oven selected for comparison for this study. The humidity within the baking chamber is determined by a balance between the moisture produced from the combustion process (in the case of gas fired ovens), the moisture removed during baking, and the extraction rate from the oven. Comparing direct gas fired and electric ovens, an electric oven can achieve a wider range of operating humidity conditions as extraction of combustion gases is not necessary. The airflow around both ovens would be expected to be influenced heavily by any fans and the belt motion, and therefore comparable with the same features.

While the primary focus has been on efficiency savings to realise emissions reductions and commercial viability, an additional consideration for electric ovens are the infrastructure impacts associated with the size of electricity supply needed. An electric oven would be expected to have a lower maximum power output, due to external constraints such as the power available from the grid. This means that the ramp up rates for an electric oven with the same thermal mass would be slower than for gas, particularly if there were multiple electric ovens that would need to start simultaneously. Electric ovens are believed to produce a more stable temperature due to the integration of sensors into feedback loops within the oven.

The optimal conditions for balancing product quality with energy consumption are not fully understood. Therefore, a new installed oven would have to be able to replicate the conditions of the gas oven with some flexibility to optimise the parameters.

Equipment Selection

To map the parameters along the length of the oven several sensors were required, all being able to record in the correct range and withstand the oven conditions. The Scorpion data logger and sensor system was selected as it is specifically designed for oven characterisation. Using the same timestamp for all the parameter sensors enabled the identification of effects from different features of the oven such as recirculation fans or moving between zones.

In addition to the primary sensing tool, an IR moisture tester was used to determine the final product moisture content. This was used as supplementary information to better understand the data from the Scorpion, such as the oven humidity profiles.

Testing Approach

To best capture the oven baking chamber characteristics, the following approach was taken:

- A space for the Scorpion was cleared on the infeed conveyor
    - The space created was as close as possible to the Scorpion's size along the moving belt
    - For ease, this was created at the edge of the belt

Figure 2 – Scorpion placement diagram (probes optional)

- The Scorpion was placed on the infeed conveyor to the oven with product surrounding it to closely mimic thermal loading of standard production conditions
- The oven conditions at the time of the Scorpion run were collected to improve the understanding of the data-set. This included:
    - Oven temperature settings
    - Oven pressure settings
    - Product throughput
    - Extraction settings
    - Recirculation settings
    - Product Initial moisture content
    - Product final moisture content
    - Average weight of product before and after

Multiple runs were conducted with both types of products with multiple batches to attempt to quantify the variability in states. The understanding gained of the variability of baking conditions while producing quality product would set the operating window for a replacement. Additionally, observing features such as the uniformity of radiation or temperature, would set a minimum for a new oven to match.

2.1.4. Oven Characterisation

Product Quality

To establish the operational window which the oven parameters could change within, a measure of product quality had to be established. Product bake quality was based on 3 key measures: colour, lift and moisture content. Operators of the oven would continually be observing product leaving the oven for product colour. In addition to this, products were sampled at regular intervals from the oven output to measure product lift and moisture. If these were found to be outside tolerance the oven would be adjusted to bring the product back into tolerance. Figure 3 shows the change in lift and colour of a product as it progresses through the oven.

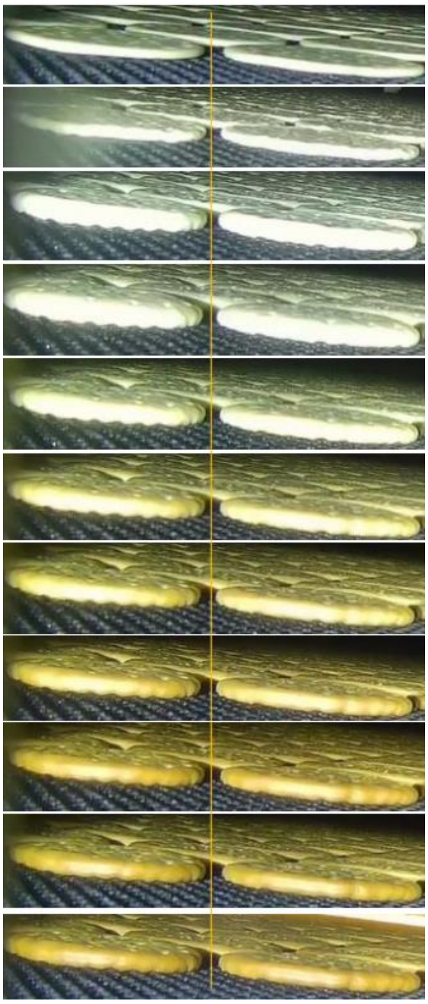


Figure 3 – Product change with time through baking chamber, images by Thistle Thermal Profiling Vantage unit on Rich Tea.

Temperature

Figure 4 shows the variation in temperature of the upper region of the oven with travel time along the oven for two days of testing. Travel time along the oven corresponds to the length along the oven and the oven zones. When the oven settings were compared between measurements, the latter half of the oven's temperature settings had been changed.

This alteration can be seen in Figure , with the disparity between the two datasets collected on different days. The first half of both traces show distinct similarities and artefacts. Similar features can still be seen in the latter half of the graph despite the temperature difference.

This data shows that although a range of temperatures can be used to create products of sufficient quality, the temperatures in steady state operation are very stable. Additionally, the non-uniformity of the temperature, believed to be due to a number of causes such as burner spacing, implies that an electric oven would also not need to display high levels of uniformity in the temperature field created.

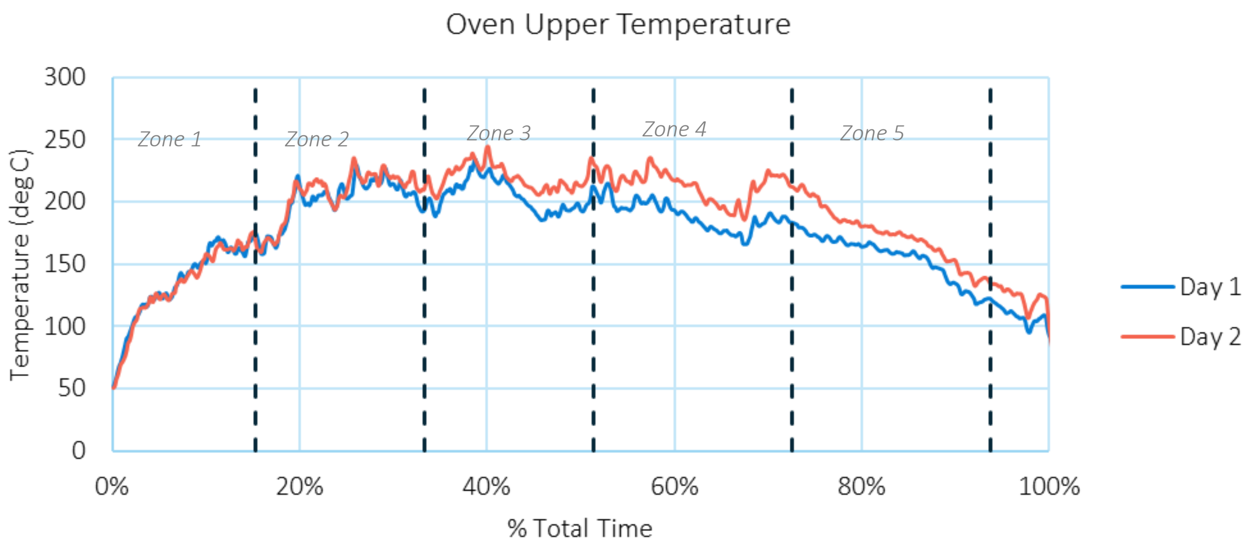


Figure 4 – Comparison of upper oven temperatures taken on different days

Heat Flux

Figure 5 and Figure 6 show aspects of the heat flux distribution along the length of the oven. Figure 5 shows the amounts of heat flux of both convective and radiative. The uniformity of the heat flux was very variable along the length of the baking chamber and appeared to increase and decrease with proximity to each burner.

Figure 6 displays the ratio of radiative to convective heat transfer across different days and oven settings. This shows that despite a larger amount of gas used and a higher temperature in one of the zones, these settings have not had a significant impact on the radiative to convective heat transfer ratios. This gives some idea of the permissible variability along the length of an electric replacement oven

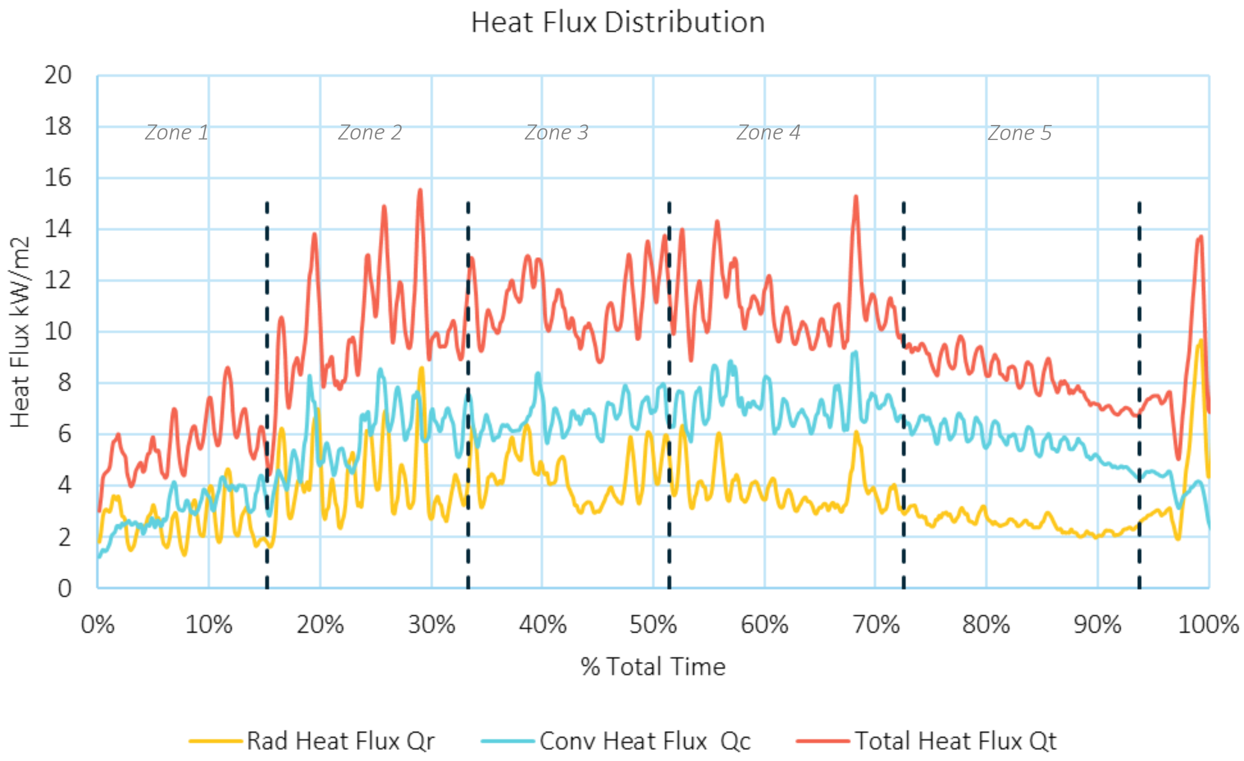


Figure 5 – Heat flux distribution for a typical oven run

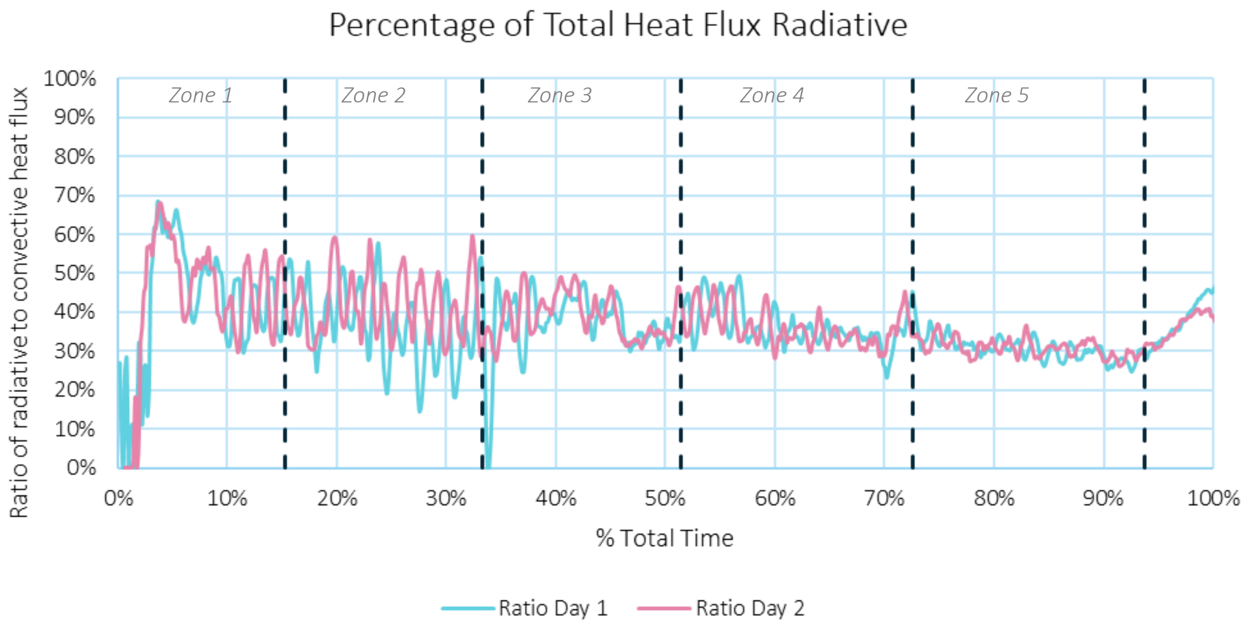


Figure 6 – A comparison of heat flux in the oven under different settings

Humidity and Air flow

Figure shows the humidity variation across the oven. The highest humidity appears around the centre of the oven. This is likely due to the air inlets being situated at each end of the oven, and the extraction near the centre, resulting in the highest humidity at the centre. Additionally, the products' internal moisture is heated as they travel through the baking chamber. This implies that the product evaporation rate will reach maximum evaporation rate in the centre as they achieve their steady state temperature. The evaporation rate then drops off as the internal moisture level reduces towards the exit of the oven.

Figure shows the air speed profile through the oven. The velocity through the oven is relatively low, not significantly above the speed of the belt. Because of the inlet and extraction locations, the product experiences a slight tailwind in the first part of its journey, and a slightly greater headwind in the latter part. A future oven would therefore only have to include a small amount of capacity to create airflow to match these conditions.

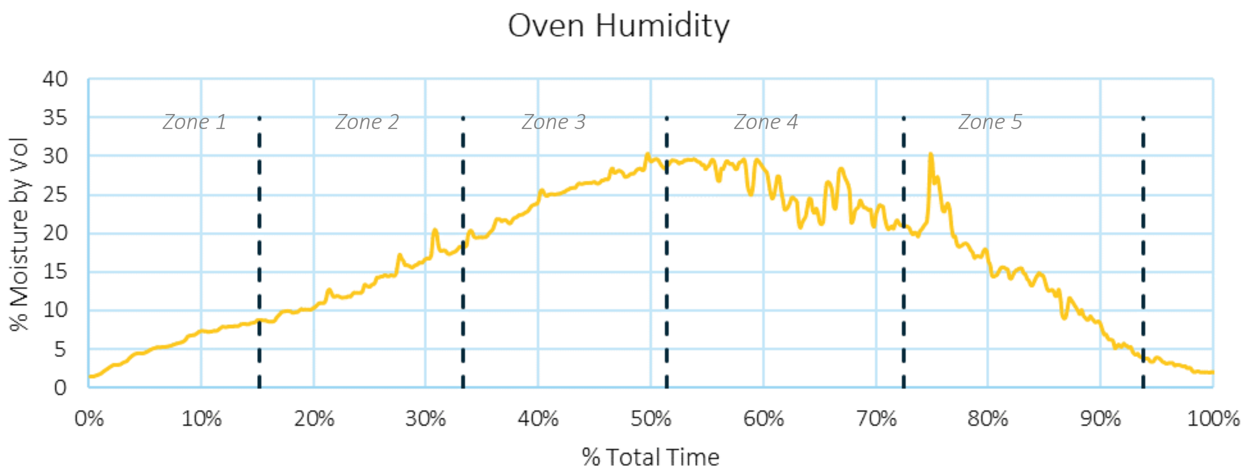


Figure 7 – Humidity across the length of the oven

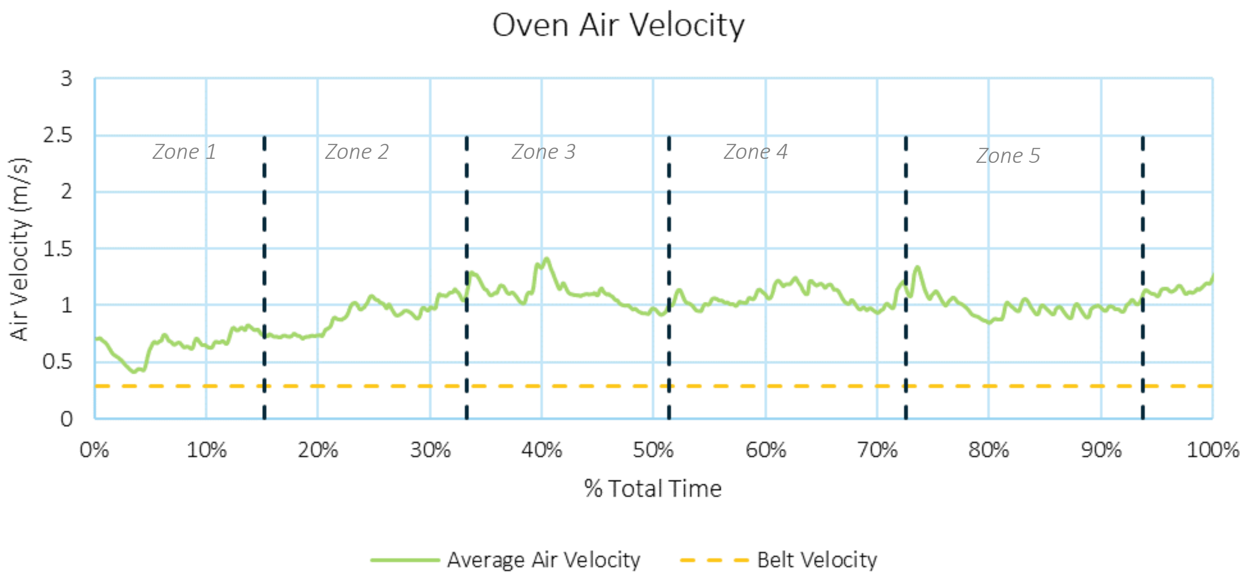


Figure 8 – Air velocity profile across the oven

Conclusions

The data collected shows various features of the gas oven. Despite the change in oven settings, the heat flux ratio remains relatively constant. Additionally, the stability of the temperature profile whilst the oven settings remained the same needs to be matched by an electric oven. These profiles provide a benchmark for the heating and airflow requirements an electric oven needs to be able to replicate.

From discussions with the operators of the ovens, much of the setting adjustment is reactionary. This therefore means that any conclusions drawn from the oven conditions are subject to the input product. Any replacement oven will be required to match the settings and stability with a moderate operating window to adjust for incoming product variation.

2.1.5. Oven Efficiency Assessment

Introduction

As part of the feasibility study to see if electric heating methods could replace natural gas for ovens, the commercial viability had to be confirmed. To avoid substantial increases in product cost transferred to the consumer, a new electric oven would need to be more efficient than the current model due to the higher cost of electricity per unit of energy. Additionally, a more efficient oven would draw less power reducing the infrastructure change required to support it. The available grid capacity is believed to be a significant constraint for the potential rollout of electric ovens.

The current oven was assessed for efficiency as a benchmark for comparison. Using this, the cost increase or reduction could also be calculated, confirming if the switch to electric would be commercially viable and allowing the installed capacity required to be estimated.

Method of Assessment

To build up a picture of the different energy sinks, a heat and mass balance model was constructed for the current oven. As a starting point the gas into the oven was measured.

The energy delivered to the food was then estimated using the recipe and the mass flow rate of product passing through the oven. The water heated and evaporated from the food was estimated using the water content of the product measured before and after the baking process. Using the internal conditions of the oven, such as extraction rate, temperature, belt speed and thermal capacity, the other losses were calculated.

Heat and Mass Balance Model Categories

The energy breakdown was categorised, each with a different potential for reduction or recapture:

Core Cooking Process

Heating food: The recipe for the product was used to calculate the energy used to raise the constituent ingredients to the product temperature upon exiting the oven. Water was considered separately from this as most is removed from the product during baking and was a very significant percentage of the total energy. The water that remains in the product after it has been baked is accounted for here.

Heating water: The energy used to heat the water in the food to the oven temperature. This is the sensible heat of the water and not the latent heat.

Evaporating the water: The energy used as latent heat in the water vapour evaporated from the product.

Energy Losses

Oven band: The oven band has a thermal mass that needs to be increased to the temperature of the oven as it enters. As it exits, it is cooled and brought around underneath the oven before collecting new products and re-entering.

Air exhaust: The current oven has a high extraction rate, meaning a large volume of replacement air must be continually heated to the desired oven temperature.

Combustion products exhaust: The energy loss from the combustion products absorbing energy from the combustion process including the latent heat from the steam created in combustion

Conduction & other losses: The remaining unaccounted-for energy, believed to be primarily lost through the oven fabric.

Figure shows the energy use split between these categories:

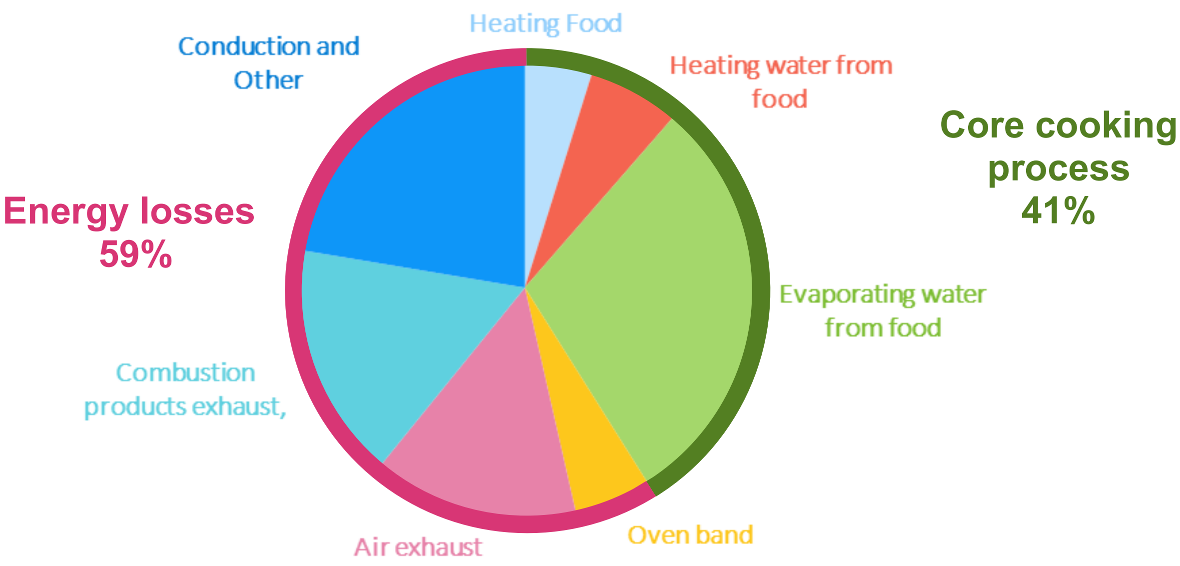


Figure 9 – Oven power usage breakdown for rich tea biscuit production

Conclusions

The energy breakdown shows that the oven is around 41% efficient. The core oven processes that this efficiency is derived from are those that heat the product itself and evaporate the moisture within it. This leaves potential for significant reductions in energy usage. The largest uncertainties in the results are the conduction losses which are derived from the remainder of energy that is unaccounted for. This means that any error in estimations from other parts of the system, for example any burner efficiency losses, would be attributed to the insulation. However, from discussions with oven suppliers following the completion of the mass and energy balance, the fraction of energy loss through conduction with respect to input power would be considered standard.

2.2. Regulatory Feasibility

Our bakeries are predominantly located in developed urban areas, predicated by the need for a workforce and good transport links. All current gas combustion exhausts are within current consent limits, but would be eliminated if baking switched to electrical sources of heat.

Eliminating gas combustion in ovens removes an explosion hazard, as well as the associated compliance activities to manage the risk to an acceptable level. This includes potential leaks from supply piping, as well as within the oven equipment itself. We already manage risks associated with electricity, so no corresponding increase arising from the fuel switch is anticipated and it would allow concentration of skills and training.

A likely outcome of the development of optimised electric baking systems is a reduction in surface temperatures of the equipment, which in addition to the energy loss benefits improves occupational safety.

Thermal losses within the bakery contribute to elevated temperatures and increased load on cooling systems, particularly during the summer. By decreasing those losses, the incremental impact on other power consumption can be reduced. The potential impact of additional heating being required in winter can be mitigated if needed by utilising recovered heat in an efficient manner.

2.3. Potential Solutions and Performance Assessment

The existing oven energy breakdown shows the loss areas and inefficiencies. Within the breakdown there are some energy sinks that are essential for product production and areas with differing degrees of opportunity for reduction.

Heating the food is an essential part of the baking process for the chemical reactions to take place, meaning energy had to be imparted into the dough. Similarly, heating and evaporating the moisture within the dough is an essential step. However, the water leaving the dough as steam has potential for energy recapture from the exhaust stream.

Switching from gas to electric also has some inherent energy savings, such as the thermal losses from extracting the combustion products would be removed.

For the remaining non-essential energy sinks, there is scope to reduce the losses through technology improvement for replacement, change in method of operation or additional technology that could be added.

2.3.1. Air Extraction Losses

The energy removed from the baking chamber represents a significant portion of the energy lost from the baking process. The air extraction requirements for electric ovens are lower than for gas ovens, due to the lack of combustion products that could be released into the factory environment. Without the combustion gas safety constraint, the extraction becomes humidity driven.

The product releases steam within the baking chamber. The desired humidity to create a quality product will therefore set the rate of air intake and exhaust, although practically this is likely to be limited by the need to maintain a negative pressure within the oven to stop steam spilling out into the factory.

2.3.2. Conduction Losses

The heat and mass balance shown in Figure of the current oven make the losses from poor insulation to be a significant portion of the overall energy loss. This could be one of the simplest areas for energy saving, as simply updating the oven to a modern design could have a drastic reduction on the energy consumption.

2.3.3. Oven Band Losses

The oven band presents one of the smaller areas for improvement of the non-essential losses. The oven band needs to be cool when products are deposited to avoid heating the dough from below too quickly, causing product defects. As heat conduction into the product from the band is a key mechanism for the quality of the product, this is an unavoidable loss. The challenges involved in recovering the heat from the moving band compared to the value of the recoverable energy mean that it has not been considered as a valid option. This could be a potential solution for a different type of oven, such as a cracker oven, that requires a heated belt for the product infeed. The belt return would then be insulated on the underside of the oven to prevent heat loss to the environment.

2.3.4. Water Evaporated from Food

The largest sector identified in the current oven by energy consumed is the input required to change water in the product into steam. If this energy can be extracted condensing the steam and recovering the heat for other applications, this has the potential for a significant increase in overall oven efficiency.

Two options were considered for waste heat recovery: hot water production, and energy regeneration.

Hot Water Production

Hot water generation utilises more of the waste heat but requires a demand for hot water or process heat nearby. Due to the contaminants present from the baking process, such as volatiles released from the products, there needs to be a heat exchange process or a filtering process. This prevents contamination or build-up within downstream processes which are harder to access for cleaning. The heat exchanger type selected also needs to be easily cleanable and resistant to the effects of contaminants.

There are therefore different options for heat exchangers that offer different benefits, either in cost or performance with ease of cleaning that is essential for this application.

Table 3 – Heat exchanger comparison

Technology	Advantage	Disadvantage	Fouling Resistance	Maximum Efficiency
Plate heat exchanger	Compact size and mature technology. High efficiency.		Gasketed plate heat exchanger allows for easy cleaning	90%
Shell and tube heat exchanger	Well understood and can withstand wide range of temperatures and pressures	Lower thermal efficiency than other options	Contains dead zones on the shell side, which can lead to fouling problems	40-60%
Economiser	High efficiency possible	More complex system requiring more new components	Anti-fouling as components taken into water waste stream	Up to 100%
Recuperators	Simple	Must be demand for incoming heat into the oven	Would require regular cleaning	Highly variable depending on application

From the available options, economisers present the most attractive option for recovering energy for process heating.

Economisers spray cooling water into a chamber containing the flue gas, including the steam. This absorbs both the latent heat and the specific heat by cooling the flue to a temperature where the water is once again liquid. It can then be passed through a heat exchanger for the next process. If the water can be recycled back into the economiser sprayer water feed a very high efficiency is possible. [2]

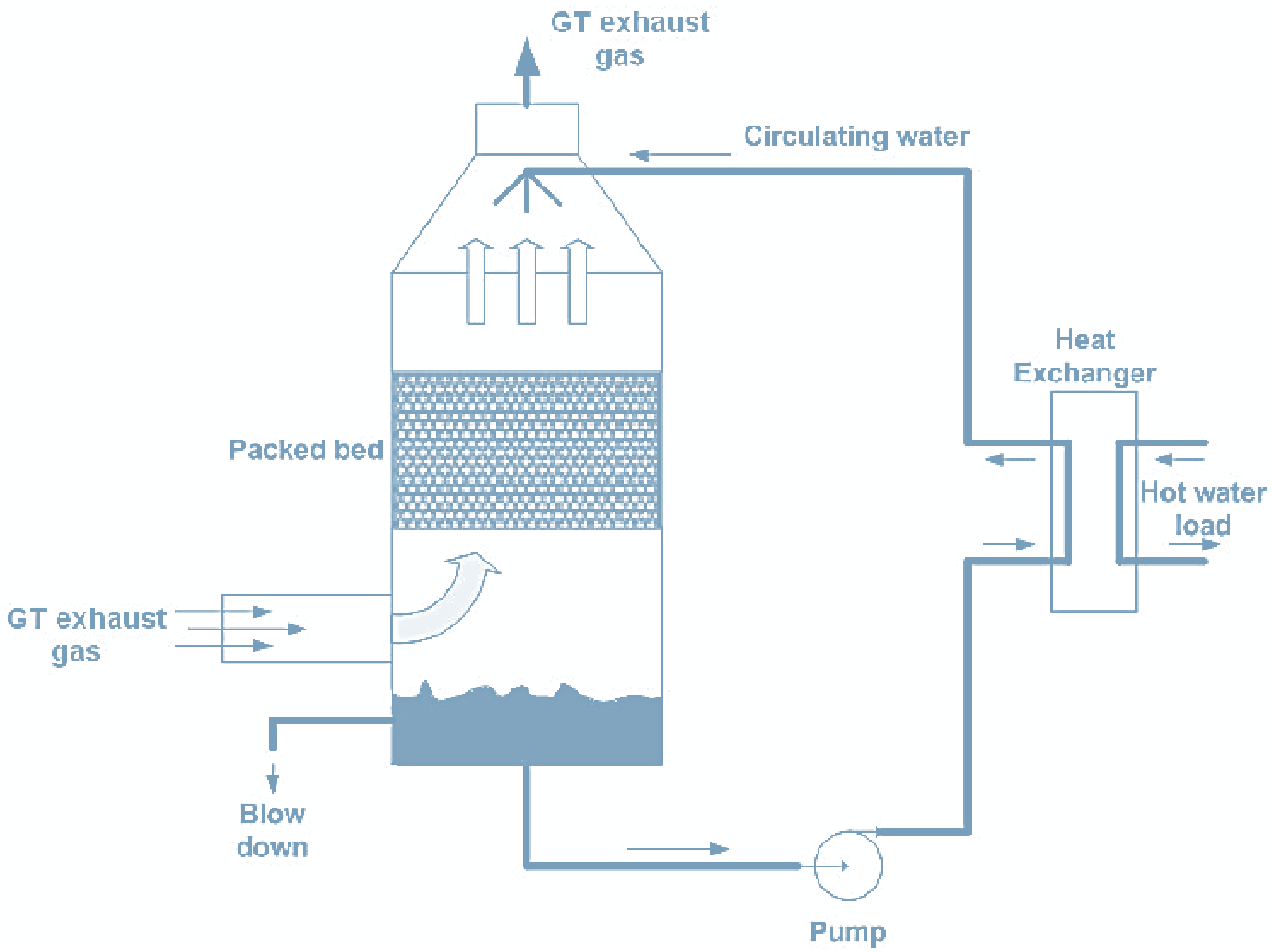


Figure 10 – Direct contact economiser working principle

Energy Regeneration

If there is excess waste heat above the process heat requirements, energy regeneration is an option to utilise some of the excess. Energy regeneration would turn excess heat back into electricity for re-use. This would also be beneficial as it would reduce the grid infrastructure capacity that would be required to power the oven. Whilst this would not be required for a single electric oven within the facility, the full conversion of a factory would produce far more waste heat than could easily be used for water heating or process heat.

Options for electricity regeneration include:

- Organic Rankine cycles
- Kalina cycle
- Super critical CO_2 cycle
- Variable phase cycle

Table 4 – Heat reconversion technology table

Technology	Advantage	Disadvantage	Efficiency	£/kWh Capacity
Organic Rankine cycles	Adaptable to various heat sources and high TRL compared to other options. Long lifetime.	Low efficiency and high cost. Working fluids can be toxic and flammable.	8-15%	1600
Kalina cycle	Large working temperature range.	Requires high pressure, expensive with limited suppliers	12-20%	1600
Super critical CO_2 cycle	Efficient heat exchange	Low TRL	8-15%	2000
Variable phase cycle	Higher efficiency than other options and low maintenance cost	Low TRL, and high fluid flow rate	10-18%	2000

Other technologies are available but are currently cost prohibitive for commercial use.

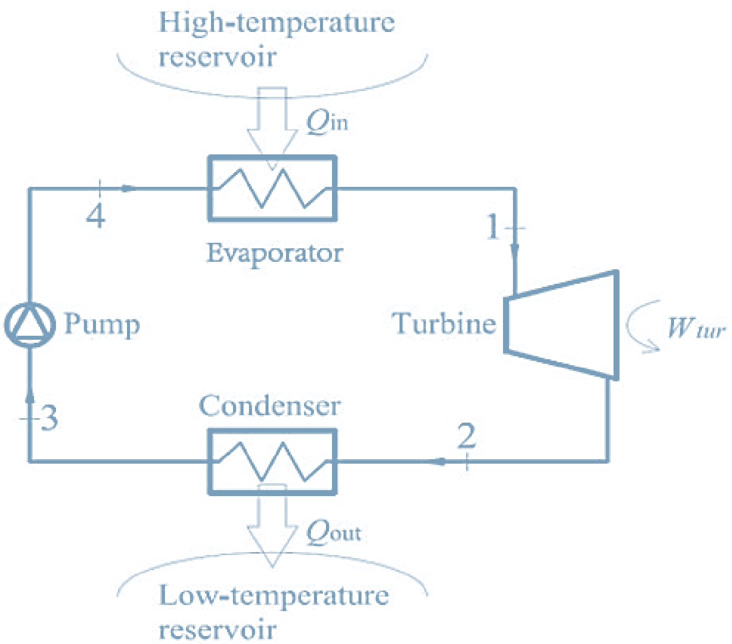
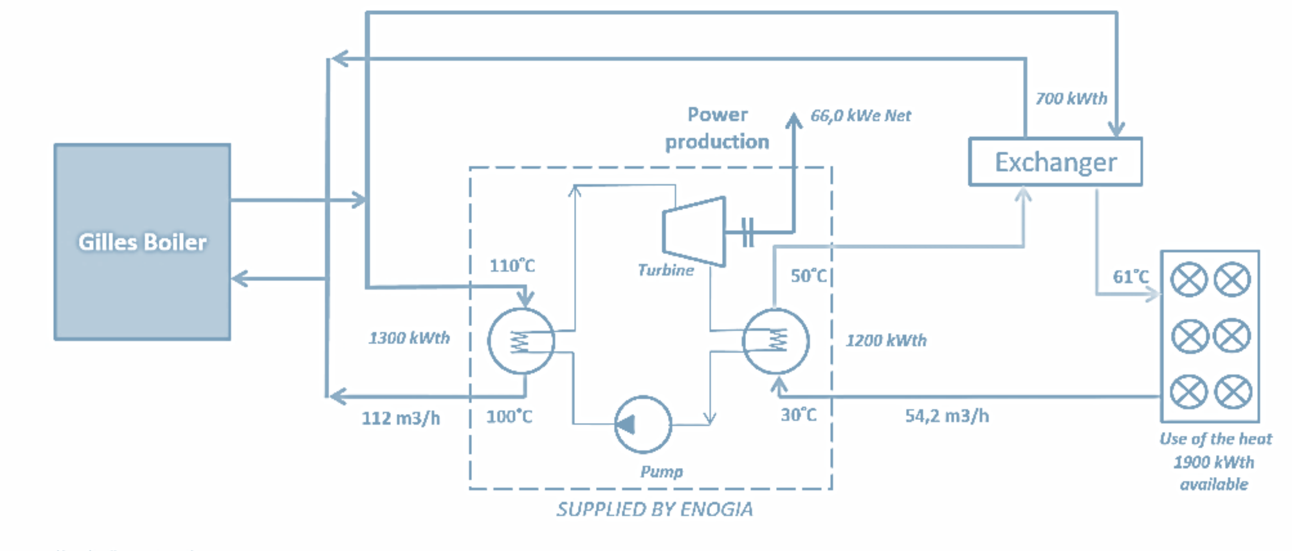


Figure 11 – Operating principle of most energy recapture cycles including organic Rankine cycle



	Biomass only	Biomass with ORC		
	RHI	RHI CHP with 40°C water	RHI CHP with 45°C water	RHI CHP with 50°C water
Eligible thermal power [kWth]	1000	1000	1000	1000
Running hours	6500	6500	6500	6500
ORC net efficiency	0.0%	5.7%	5.2%	4.7%

Figure 42 – Example system layout for heat recovery from the oven [3]

Recovery Opportunities

The process heat requirement at the Burton's Foods Edinburgh facility could be provided by the waste heat from some of the ovens. The remaining heat from the other ovens could be used for other processes such as refrigeration cycles or potentially low-carbon district heating for neighbouring industry or housing.

2.3.5. Discussions with Industry Experts

To best interpret the data that was collected from the ovens, industry experts were consulted. Mark Williamson, an industry expert with over 40 years' experience with characterising ovens, was consulted on both the Scorpion data collected and the oven efficiency assessment. For the heat and mass balance calculations performed he was able to review the model, comparing the results to other ovens he had modelled in the past. In addition to the review work he did for the project, he was able to advise on the likely success of solutions. This included estimating amounts of energy savings that would be attainable with certain solutions.

To estimate the TRL of different energy saving measures, suppliers were consulted on their areas of expertise. Several electric oven manufacturers were contacted to learn about what recent developments had been made in the field and what was commercially available. Towards the end of the study, the suppliers' energy saving measures applied to commercial electric ovens were compared against the solutions recommended. This then informed the final TRL of the study, estimating the gap between what would be required of an oven for Burton's Foods and what was commercially available.

For more detailed information on particular solutions that were not included by electric oven manufacturers, industry leaders were contacted for details. This included information on heat exchangers, organic Rankine cycles, heating elements and sensors. These companies provided application specific details to quantify the solution performance in greater detail.

2.3.6. Overall Performance Assessment

The areas where it is likely that energy savings can be achieved are listed in Table 5. The maximum energy saving potential for each reduction area and the associated level of uncertainty of achieving this are outlined.

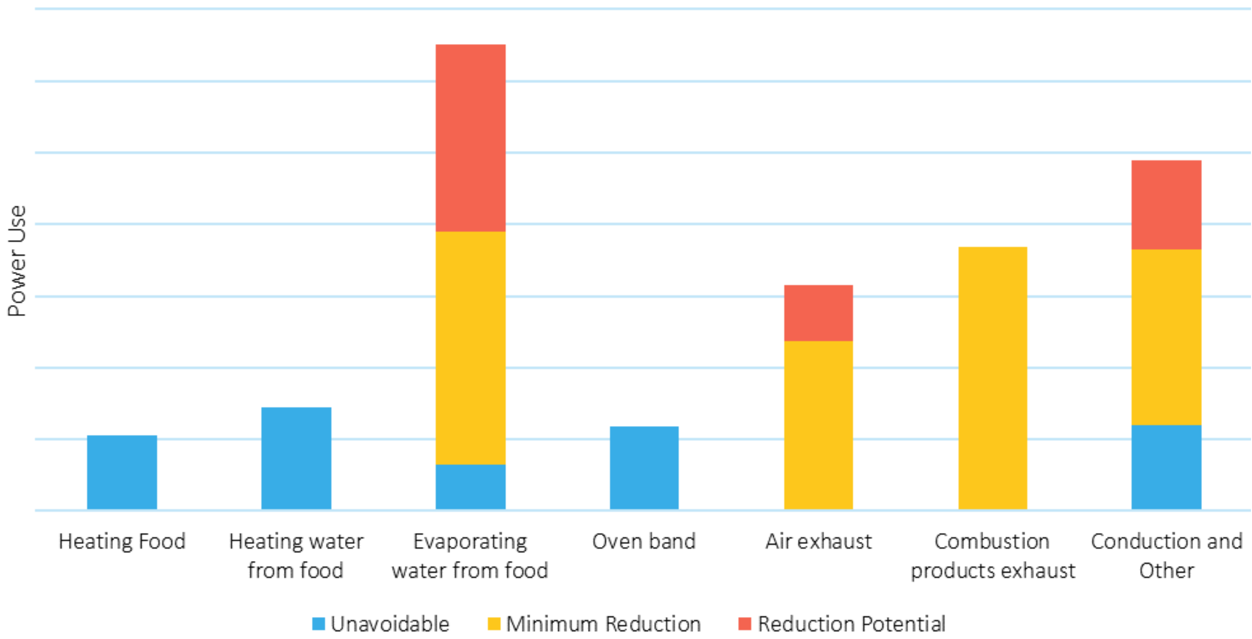
Table 5 Energy reduction category uncertainties

Category	Lower estimate potential improvement	Maximum potential improvement	Uncertainty of maximum potential improvement realisation
Evaporating water from food	50% efficiency	90% efficiency	High
Air Exhaust	75% reduction	100% reduction	High
Conduction	50% reduction	75% reduction	Medium
Combustion Products	N/A – will be 100%	N/A – will be 100%	Low

Figure shows the maximum potential energy saving in comparison to the unavoidable use and the minimum likely reduction of the recommended improvements. The unavoidable energy is that which is believed could be reduced and recovered. As some energy is recovered from the baking process itself, it therefore means that an oven with the maximum potential improvement would have an efficiency above 100 percent.

Figure highlights that the majority of the savings are due to the heat recovery processes. This is a maximum savings potential and would need to be validated experimentally. However, this result shows great promise for the commercial feasibility of electric ovens.

The total maximum reduction potential in energy is **75%.** The total minimum potential is a reduction of **54%**. Figure highlights the split of the reduction potential contributions for each of the different categories of heat loss.



Category	Unavoidable	Maximum Reduction Potential	Minimum Reduction
Heating Food	5%	0%	0%
Heating water from food	7%	0%	0%
Evaporating water from food	3%	27%	15%
Oven band	5%	0%	0%
Air exhaust	0%	14%	11%
Combustion products exhaust	0%	17%	17%
Other (conduction)	5%	17%	11%
Total	25%	75%	54%

Figure 13- Potential energy savings by category

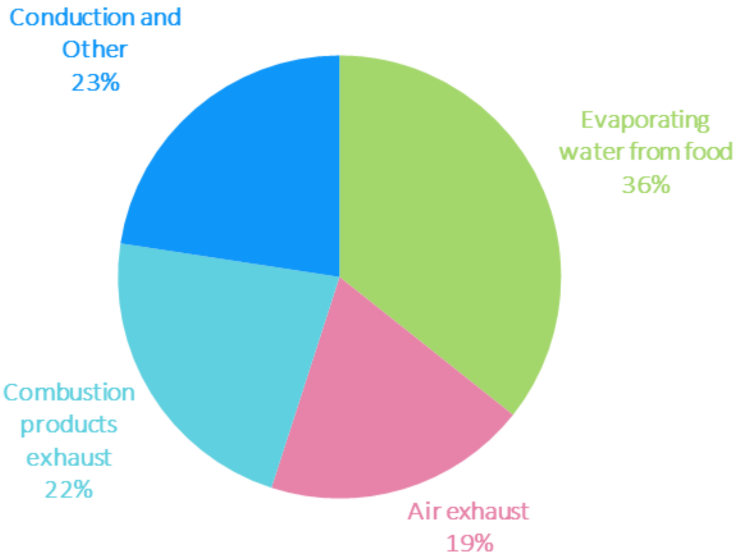


Figure 14 – The reduction potential contributions for each of the different categories of heat loss

The cost of natural gas and electricity in the UK is extremely volatile currently and difficult to forecast future rates, however the ratio between the cost of natural gas and electricity varies in the range 3.9 to 2.9. To achieve parity with current gas costs, the oven would need an energy saving between 74% to 66%, which is at the upper end of the predicted maximum reduction in energy consumption of 75%.

2.4. TRL at the Start and End of the Project

The primary uncertainty at the beginning of this project was the availability of technology that would make electric ovens commercially comparable with gas fired ovens, given the substantially higher cost of heating. This study has shown that electric ovens, if installed with high efficiency heat recovery systems could be commercially viable to replace gas fired ovens. In addition, the technical question was raised if electric ovens would be able to produce the same quality products as gas fired ovens. Discussions with vendors have confirmed that electric ovens are capable of this.

At the beginning of the study, it was uncertain if electric ovens would consume the same power as a gas oven. Historically, ovens have been optimised to produce quality products with safety margins without the energy usage as a major consideration. This study has shown that more modern ovens have improved conduction losses and improved sensing capabilities for monitoring the baking conditions. This study has also shown that many of the savings are achieved through changes to the way the oven is operated, such as running at the maximum humidity possible.

2.4.1. Vendor Discussions and Assessment

To fully assess the TRL and commercial viability of an electric oven replacement, a requirements specification was created. The requirements would be used to compare against the performance of existing ovens. The difference between the ideal and available was the technology gap that would need to be bridged to make this technology viable for Burton's Foods to pursue.

The requirements matrix was comprised of a mixture of general and technical requirements primarily informed by the Scorpion testing performed on the current example oven.

In addition to the requirements specification, a supplier assessment criterion was devised. This criterion helped guide discussions with suppliers to assess their current solutions.

Figure 5 – Vendor Assessment Criteria

The suppliers approached all had experience in some form with electric ovens and were all of a large enough size to be able to perform the required research and development work to improve performance.

These discussions led to comparison of their designs against the requirements matrix and the heat and mass balance that had been constructed to estimate how close to the ideal oven they were.

2.4.2. Commercial Availability of Potential Solutions

Electric ovens that can produce similar or the same types of products to gas-fired ovens are currently commercially available. A series of suppliers, with prior experience in the field have confirmed this, providing quotes and performance estimates for their available ovens. One of the suppliers contacted gave a range of figures for the power consumption that overlapped with the estimations for an efficient oven that didn't have heat recovery from the steam. This implies that there are significant savings that can be made with improvements in conduction and air extraction monitoring and control. The improvements mentioned, as they are commercially available may imply a high TRL, however the actual performance of these improvements without being tested or without data provided for comparable product production still leaves some uncertainty.

Heat recovery is required for this system to be commercially viable as the majority of the energy savings are realised by this technology. Without heat recovery energy savings, the higher cost of electricity makes switching prohibitively expensive. The combination of high efficiency electric oven with steam heat recovery is not available as a package and would have to be combined from separate vendors. Therefore, a combination of the electric oven with a high efficiency heat exchanger for process heat would have to be developed. As both systems are individually up to TRL 9, proven in an operational environment, the combined TRL of the technologies would be TRL 6. Both technologies have been tested in relevant environments, but require a prototype demonstrating that they work in combination in the relevant environment to move to the next TRL.

2.5. Carbon Emissions Savings Potential

The increased efficiency of the electric oven proposed above this would save around three quarters of the power consumed. Scaling a roll-out across all ovens in Fox's Burton's Companies UK bakeries would reduce emissions by up to 17,000 tonnes CO_2e per year.

3. Dissemination Plan

Aside from direct replication from the initial pilot production line across all seven bakeries in the combined Fox's Burton's Companies group and potentially other business owned by Ferrero, disseminating learnings from the feasibility study could be done through bodies such as the Food and Drink Federation to ensure competition law is respected.

Key stakeholders are equipment vendors, who will be the main route to disseminating how other companies can benefit from the outputs of the study and subsequent Phase 2 implementation. It's likely that there will be much more meaningful opportunity to share learnings after Phase 2, due to the requirement to develop system solutions based on the characterisation studies prior to implementation.

4. Social Value

The potential fuel switch across all of our bakeries (located in England, Scotland and Wales) would require training for operators and maintenance staff in each location, as well as our product development teams to understand the differences from gas-fired ovens. Having better control of the baking process may even allow development of innovative biscuits that couldn't be developed with existing equipment.

Vendor partners would increase their workforce to satisfy the expected demand in electric ovens and a significant proportion of that value being delivered by UK-based labour.

With the broader electrification of heat across industry, it is anticipated that suitable foundation education programmes will be created that would assist in developing our workforce and complement the specific elements related to oven operation and maintenance.

A successful transition will protect existing roles within our teams and facilitate training to higher levels of technical competence without the safety hazards associated with natural gas combustion.

Many UK and global retailers and consumers are requesting net zero supply (e.g. Tesco by 2035) – this project will enable that demand to be met from a UK supply base, maintaining competitiveness, UK revenue, jobs and skills. It would also promote demand for electric ovens, which may be serviced by UK based suppliers – the UK has a strong food production equipment supply chain who export globally, a position that would be strengthened as other countries transition to electric baking.

Burton's Foods Limited currently exports some production outside of the UK. There is a risk that lower cost biscuits produced outside of the UK displace local manufacture if customers and consumers value purchase price over sustainability credentials unless an effective carbon price border adjustment programme is in place.

5. Phase 2 Demonstration Description

5.1. Feasibility Study Outcomes & Demonstration Options

This feasibility study has looked at the technical and commercial viability of switching the fuel source of commercial biscuit baking ovens from gas to electricity while maintaining the current product qualities. The headline outcome of the study is that while on a technical level switching to electricity is feasible, efficiency improvements are needed to make switching commercially viable.

Some opportunities to improve efficiency and enabled the switch to become commercially viable have been identified. The key opportunities that have been identified are introducing heat recovery and enhancing the ability to control the oven by better linking the oven and product conditions.

The next step needed to enable switching will be to demonstrate performance in full production conditions. This would progressively consider the full range of product types and assess the energy performance in practice, allowing the understanding of the commercial viability of production to be refined. This would constitute a demonstration of the viability which would give the confidence necessary to proceed to full roll out of the solution.

5.1.1. Phase 2 Demonstration

Overview

The aim of the project will be to work with a partner to commission a pilot line to prove the performance levels necessary to extend to a roll out across the bakeries.

Prerequisites

- Select and reach agreement to proceed with a suitable partner(s)

Opportunities & Risks

Opportunities	Risks
✓ Performance improvement over what is currently commercially available ✓ Program likely to be achievable with Phase 2 budgets and timescales ✓ Capitalise on experience of experts	✗ Product and technical constraints may limit the performance possible in practice, either impacting commercial viability to switch fuels or increase impact of local grid capacity constraints

5.1.2. Heat Recovery Integration

Overview

There is an opportunity to achieve significant savings from heat recovery. This work package will determine the optimal split between hot water and energy generation based on the factory demand for heat. Work will then be carried out with heat recovery vendors to optimally integrate heat recovery into the oven design. On completion, testing of the efficiency gains achieved in practice will be carried out.

Prerequisites

- Selection of heat recovery vendors

  Some work will be required to identify a suitable and willing heat recovery vendor. If this can be agreed in advance of the project, then it will lead to significant reductions in risk and allow a much more accurate programme and costing to be put forward.

Opportunities & Risks

Opportunities	Risks
✓ Likely to be choice of vendor partners ✓ Integrate well established technology into an oven context, so technical risk is moderate and aspects such as maintenance and fouling are understood	× Balance between needs for hot water and proportion of energy recovery needs to be established in order to optimise overall oven efficiency gains

5.2. Interim Preparatory Work

Some further interim work subsequent to this feasibility study will be required to complete the outlined prerequisite activities develop a fully agreed programme and cost estimate.

5.3. Wider Rollout Context

The route to the wider production rollout of electrification is summarised in Figure 6.

Feasibility Study
Assessment of technical and comical viability of baking biscuits with electric ovens Define next step options

↓

Pilot Scale Demonstration
Determine in operation performance in practice Test ability to produce a range of products De-risking of technical risks associated with any new design elements Advise most commercially viable route to delivery of a full-scale oven

↓

Production Scale Rollout
Deliver production scale version of Phase 2 demonstration design Roll out new oven design across all production lines

Figure 68 Route to full production roll-out

6. Phase 2 Details

6.1. Explanation of how the Demonstration will Enable Industrial Fuel Switching

Switching fuel for ovens from gas to electricity requires both the availability of sufficient power and the cost impact to be manageable to deliver the transition, as well as assurance that biscuit quality and production throughput rates can be maintained or improved. Due to the complexity of bio-chemical and physical structure changes during the baking process that are specific to recipes and product types, whilst modelling and analysis of a new oven design gives an indication of performance it is not sufficient assurance to progress immediately to a full-scale oven roll-out and be confident the cost & quality impact will be acceptable.

6.2. Benefits and Challenges

Benefits	Challenges
✓ Demonstration of feasibility, allowing d roll-out potential to be validated ✓ Opportunity to measure actual performance and improve if necessary, before committing to a full-scale roll-out ✓ Quicker roll-out may be possible (subject to grid capacity constraints) by early demonstration	× Implementation costs need to be controlled within limits × Design solutions may be needed to sustain required performance × Solutions need to be delivered by March 2025, so limited time to accommodate delays

6.3. Process Risks

The top key projects risks associated with the proposed Phase 2 demonstration are as follows:

Classification		Risk Details			Evaluation			Management Action Required
ID	Category	Title	Description	Existing Mitigations	Severity	Probability	Score	Strategy
1	Project Management	Delivery timescales	The timescales to deliver the project are very tight, with a hard deadline for the BEIS funding. Any delays will make delivery challenging		3	3	9	Limit
2	Project Management	Critical team members dependency	Success is dependent on competent partners and their expertise	Careful partner selection, suitable back-up plans	3	3	9	Limit

Classification		Risk Details			Evaluation			Management Action Required
ID	Category	Title	Description	Existing Mitigations	Severity	Probability	Score	Strategy
3	Economic/Financial	Cost uncertainties	Costs are being estimated in advance and are subject to significant volatility	Include contingency	3	2	6	Accept

6.4. Potential for Scale-Up Against a Counterfactual

A counterfactual example to the options proposed in Section 5 would be a currently available electric oven without any of the adaptations discussed in this report. Based on the understanding gained of the electric ovens that are currently available, there would be an efficiency improvement equivalent to an energy consumption reduction of around 25%-30%. This is significantly less than the improvements of 75-54% explored it in the options presented in this study.

7. Phase 2 Project Delivery Plan

If successful with funding in Phase 2, a full-scale electric oven would be installed at a facility and connected to upstream processing and downstream packing operations. This will allow the performance to be validated and a business plan to transition other production lines in the FBC UK group. The pace and sequencing of the transition will depend on several factors:

- Proven energy efficiency of the oven
- Market prices of electricity and natural gas
- Completed trials of the biscuit type to verify oven requirements
- Available electrical capacity at each location
- Commitments to reduce emissions
- Consumer demand for lower-carbon biscuits
- Availability of capital investment funds
- Downtime requirements to transition each line and maintaining customer service

Having the facility created through Phase 2 significantly reduces the risk of transitioning to electric ovens and enables a faster roll-out if required.

8. Route to Market Assessment

8.1. Key Steps to Commercialisation

It is anticipated that beyond the initial full-scale oven implementation considered in a Phase 2 application, adaptations would be made accordingly based on learnings that can be readily integrated to form future deployments across all bakeries.

8.2. Significant Barriers and Risk

Barriers and Challenges	Potential Mitigation
Supply chain risk - manufacturers not used to producing the volume of ovens required for a full industry switch in a short time frame	Discussions with suppliers and stakeholders about likely timescales for a roll-out
Insufficient renewable electrical supply capacity at all or some locations of bakeries	Dependent on broader investment in national infrastructure for electrification generation and distribution and availability at bakery supply connections, some local network reinforcement may be economically viable subject to cost Maximising energy efficiency
Upgrades required to bakery electrical infrastructure to accommodate increased load	Necessary investment considered within deployment cost planning, ongoing electrical efficiency programmes at each site reduce baseload
Uncertain heat recovery efficiency and reliability – risk of fouling during long-term operation	Phase 2 implementation would assess this fully and determine how to resolve satisfactorily
Having sufficient demand for recovered heat to maximise new oven energy efficiency	Investigation into alternative options for waste heat utilisation

8.3. Rollout Potential and Potential Carbon Savings

The primary carbon savings for other sectors from the rollout of this solution are the energy saving methods that make electricity a viable fuel alternative. There are many industries that require product or water heating that would not be commercially viable to switch to electric heating directly. Industrial heating systems such as other ovens, dryers, heaters and furnaces have the potential to benefit from this study. The carbon emission reduction from switching to electric could be substantial. The greatest savings would likely be from other areas of the food and drinks industry which would have the most similar production to this study.

The FDF report into decarbonising heat estimates annual emissions of approximately 700,000 tCO_2e from direct fired ovens in the UK food & drink sector could be decarbonised, with a similar level of emissions associated with other direct fired processes too [1]. The pace of the rollout was also estimated in the same report.

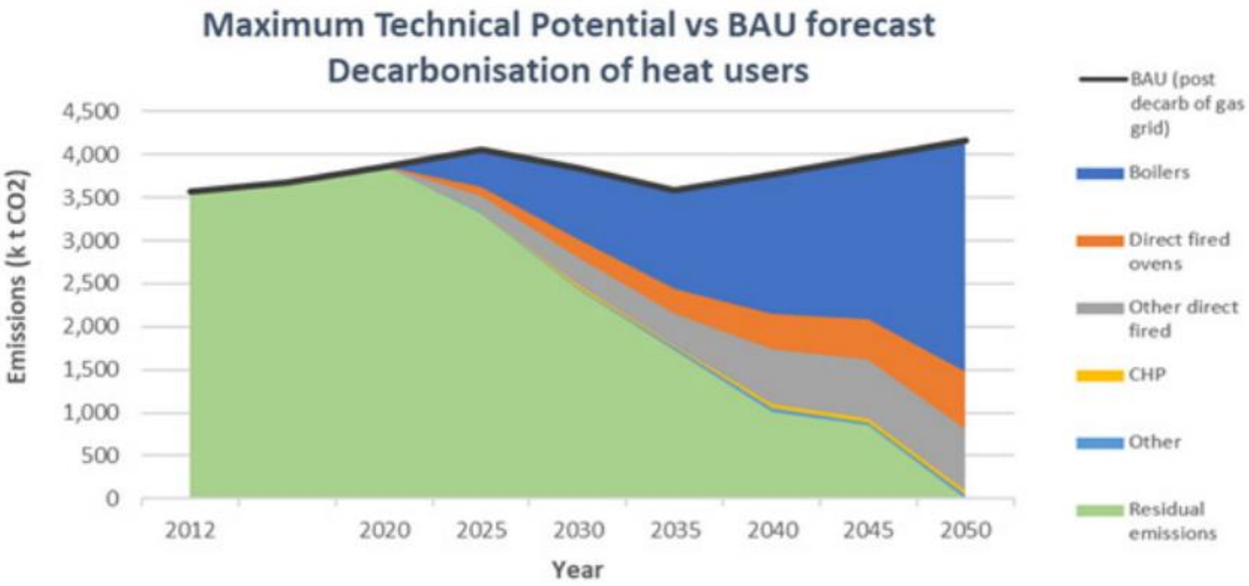


Figure 19 Maximum technical potential vs BAU forecast decarbonisation for heat users. [1]

Table 6 FDF Report: Estimated percentage of replacements switching to decarbonised alternatives. [1]

Timeframe	Boilers	Direct Fired Ovens	Other Direct Fired	CHP	Other	Reasoning
2020-2025	20%	20%	20%	10%	20%	• Cost of alternatives not yet competitive enough and like for like replacements made. • Lack of knowledge or confidence in electrification of some processes. • Availability of renewable sources. • Uncertainty about future energy sources.
2025-2030	50%	40%	40%	20%	40%	
2030-2035	75%	50%	70%	70%	70%	• Cost of alternatives not yet competitive enough and replacement cycles are delayed. • Supply of decarbonised gas or hydrogen not yet established. • Availability of renewable sources. • Lack of knowledge or confidence in new technologies. • Product quality compromised with alternatives.
2035-2040	85%	60%	80%	80%	80%	
2040-2045	90%	75%	85%	85%	85%	• Cost of alternatives not yet competitive enough and replacement cycles are delayed. • Supply of decarbonised gas or hydrogen not yet established in less populated areas. • Product quality compromised with alternatives.
2045-2050	93%	90%	90%	90%	90%	

8.4. Potential Benefits for Other Sectors

Areas that would be developed within Phase 2 could also be relevant for other aspects of the food and drink sector, such as demonstrating heat recovery from exhaust gases with particulate and volatile components present that can cause fouling and safety hazards and increase the TRL of that technology for low grade heat recovery. The potential scale is very large, with "2.8 TWh of recoverable waste heat is emitted to environment from the food processing industry per annum of which at least 85% is of low-grade" [8]. This would also be applicable to other sectors with low grade heat estimated to affect up to 50% of all waste heat.

Similar oven-based operations exist in several other sectors, both for curing and drying purposes and include ceramics, composites, paper, automotive (paint) and potentially heat treatment applications as well, with the principles being developed likely to have an element of cross-sector application.

8.5. Assessment of Job Creation

Increasing electric oven energy efficiency raises the likelihood of a faster and greater scale transition from baking biscuits with natural gas fired ovens. In addition to creating roles in the equipment supply chain of the ovens themselves (number of roles dependent on scale and pace of rollout), it will help secure existing employment in biscuit bakeries by enabling the transition of the hardest unit operation to decarbonise in line with the expectations of consumers and customers and regulatory / business requirements.

9. Feasibility Study Conclusions and Performance Against Objectives

All the objectives of the feasibility study were undertaken successfully. An example oven within the Burton's facility was characterised by mapping how the identified key variables changed through the baking process within the chamber. The characterisation gave an operational window, showing the limits of the key variables that could create products within the quality thresholds. The characterisation also enabled potential vendors to give a more accurate picture of their technology offerings for the requirements of the example line.

The vendor discussions showed that electric ovens exist that can produce products to an acceptable quality level. However, the discussions also highlighted that the technology available from vendors would not be commercially viable with current energy prices. The technology available has not been optimised for energy saving and operational cost reduction. By improving energy efficiency and implementing heat recovery it is feasible to reach performance levels that are viable to roll-out a fuel switching programme.

10. Bibliography

[1] FDF, “Decarbonisation of heat across the food and drink manufacturing sector,” 2020.

[2] T. M. a. T. Z. Vhutshilo Madzivhandilaa, “Recovery of flue gas energy in heat integrated IGCC power plants,” Department of Chemical Engineering University of Pretoria, 2010.

[3] C. B. Ltd., “Biomass Organic Rankine Cycle,” Commercial Biomass Ltd., [Online]. Available: https://commercialbiomassuk.com/combined-heat-power/biomass-orc-and-chp/. [Accessed 11 08 2022].

[4] Department for Business, Energy & Industrial Strategy, “Industrial energy price statistics,” Department for Business, Energy & Industrial Strategy, 26 June 2022. [Online]. Available: https://www.gov.uk/government/collections/industrial-energy-prices. [Accessed 19 08 2022].

[5] O. W. i. Data, “Carbon Intensity of Electricity,” Our World in Data, [Online]. Available: https://ourworldindata.org/grapher/carbon-intensity-electricity?tab=chart&country=~GBR. [Accessed 18 08 2022].

[6] Department for Business, Energy & Industrial Strategy, “Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal,” UK Gouvenrment, 7/10/21.

[7] Department for Business, Energy & Industrial Strategy, *Plans unveiled to decarbonise UK power system by 2035,* 2021.

[8] A. H. D. R. Richard Law, “Opportunities for Low-Grade Heat Recovery in the UK Food Processing Industry,” in *Sustainable Thermal Energy Management in the Process Industries International Conference*, Newcastle, 2011.

[9] N. R. J. K. M. O. Sara Drescher, “A REVIEW OF ENERGY USE IN THE FOOD INDUSTRY,” Agricultural and Biological Engineering Department, West Lafayette, 1996.

[10] E. &. I. S. Department for Business, “Gas statistics,” Department for Business, Energy & Industrial Strategy , 2022.

[11] ThermTech, “Thermtech Case Studies,” [Online]. Available: https://thermtech.co.uk/category/case-studies/. [Accessed 26 08 2022].

[12] E. S. D. H. A. Bani Kananeh, “Application of antifouling surfaces in plate heat exchanger for food production,” Schladming, Austria, 2009.

Appendix A. Activities for Phase 2 Options

The activities outlined for the Phase 2 options are dependent on the inputs from 3rd party partners who have not yet been selected. An estimate of the likely activities to meet the objectives has been created.

A.1. Phase 2 Demonstration

Oven

• Specification
  ◦ Define measurement points for energy, product and condition monitoring
  ◦ Define operation conditions
• System development
• Manufacture oven
• Installation
• Commissioning

Enabling Works
• Infrastructure works • Enabling works at bakery
Performance Testing
• Efficiency monitoring • Product testing across a variety of products

A.2. Heat Recovery Integration

Heat Recovery Integration

• Identify the heat and electricity requirements for the surrounding area
  ◦ How much process heat does the facility need?
  ◦ How much space heating is required?
  ◦ How much recovered electricity is required?
  ◦ Identify demand split between water production and energy regeneration
  ◦ Develop system specification
• Heat recovery selection
  ◦ Vendor assessment and selection
  ◦ Identify and assess value of uses for excess heat
  ◦ Component selection and process design
  ◦ Initial trials to assess performance
• Overall system design and integration with individual oven
• Install & commissioning
• Testing to confirm efficiency gain contribution from the heat recovery system

2022 © 42 Technology Limited

Appendix B. Heat Recovery Design Considerations

Heat recovery systems are heavily dependent on the process feeding into them and the composition of the inlets and outlets. With two distinct options for the recovery of latent heat from the trial facility ovens there would need to be two distinct designs for the heat recovery.

For exclusively process heat generation for other processes, it is recommended that a direct contact economiser is used due to the high efficiency and the fouling resistance. Economisers are typically used for boilers, where the exhaust flue gas is passed through the incoming water to pre-heat it before that water enters the boiler. While there are examples of economisers of the approximate size for recovering the waste heat from line 4, these are designed to operate without contaminants in the flue stream. Work would need to be completed developing a solution that resisted fouling and was able to be cleaned easily. In addition, if the water from the economiser was to be used for process heat directly, a filtering system to remove contaminants would have to be installed with design effort into the cleaning and replacement of the filters.

For example, Thermtech, a heat recovery specialist in the UK, has case studies for applications close to those that would be required for the trial facility. They include using economisers for single pieces of equipment, that would be needed for a prototype, to full retrofitted facility steam heat recovery systems in the MW scale. [11]

If the decision was made to recover some of the waste heat as electricity, a heat exchanger between the contaminated exhaust stream and the electricity generation fluid would have to be implemented to avoid contamination. A plate heat exchanger design would be the most likely for this application due to the high efficiencies and the easier cleaning compared to other heat exchanger types. This would need anti-fouling coatings to prevent short cleaning and maintenance intervals. Literature suggests a polymer coating, such as 20µm PTFE, could reduce the cleaning time by as much as a factor of 10 [12]. In addition to the coatings, a design that could potentially be removed from the flow to be cleaned would be beneficial for continual operation. This solution would also be required for any refrigeration applications.

 2022 © 42 Technology Limited

Appendix C. Log of Assumptions

General Assumptions

- All values and figures used within this document are based on current best-known values

Heat and Energy Balance Modelling Assumptions

- The testing performed was representative of all production runs on the oven
- The equipment and sensors installed on the oven were performing adequately and providing accurate data
- The recipe for the product was followed exactly

Carbon Reduction Modelling Assumptions

- Grid carbon intensity will drop in line with targets
- Condensing heat exchange energy recovery efficiency is likely to be reduced by distribution energy losses and periods where demand doesn't meet the available supply
- The electric heating elements have an efficiency comparable to the gas burners

Cost Modelling Assumptions

- Current Burton's Foods energy prices for gas and electricity have been used for all calculations
- New capital equipment will have a lifetime of 30+ years
- The cost of maintenance on the oven is similar to that of standard industrial equipment

2022 © 42 Technology Limited